Water-use dynamics of an alien invaded riparian forest within the mediterranean climate zone of the Western Cape, South Africa

Scott-Shaw Bruce C[1], Everson Colin S[1,2,3] and Clulow Alistair D[4]

[1]Center for Water Resources Research, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa.
[2]South African Environmental Observation Network (SAEON), Grasslands-Wetlands-Forests Node, 1 Peter Brown Drive, Queen Elizabeth Park, Montrose, Pietermaritzburg 3201, South Africa
[3]Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20, Hatfield, Pretoria 0028, South Africa.
[4]Agrometeorology, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa.

Abstract

In South Africa the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. Tree water-use measurements have therefore become an important component of recent hydrological studies. It is difficult for government initiatives, such as the Working for Water (WfW) alien clearing programmes, to justify alien tree removal and implement rehabilitation unless a known hydrological benefit can be seen. Consequently water-use within a riparian forest along the Buffeljags river in the Western Cape of South Africa was monitored over a three year period. The site consisted of an indigenous stand of Western Cape afrotemperate forest adjacent to a large stand of introduced *Acacia mearnsii*. The heat ratio method of the heat pulse velocity sap flow technique, was used to measure the sap flow of a selection of representative indigenous species in the indigenous stand, a selection of *A. mearnsii* trees in the alien stand and two clusters of indigenous species within the alien stand. The indigenous trees in the alien stand at Buffeljags river showed significant intraspecific differences in the daily sap flow rates varying from 15 to 32 $L \cdot day^{-1}$ in summer (sap flow being directly proportional to tree size). In winter (June) this was reduced to only 7 $L \cdot day^{-1}$ when less energy was available to drive the transpiration process. The water-use in the *A. mearnsii* trees showed peaks in transpiration during the months of March 2012, September 2012 and February 2013. These periods corresponded to favourable climatic conditions of high average temperatures, rainfall and high daily vapour pressure deficits (VPD - average of 1.26 kPa). The average daily sap flow ranged from 25 L to 35 L in summer and approximately 10 L in the winter. The combined accumulated daily sap flow per year for the three *Vepris lanceolata* and three *A. mearnsii* trees was 5 700 and 9 200 L respectively, clearly demonstrating the higher water-use of the introduced *Acacia* trees during the winter months. After spatially upscaling the findings, it was concluded that, annually, the alien stand used nearly six times more water per unit area than the indigenous stand (585 $mm \cdot .yr^{-1}$ compared to 101 $mm \cdot yr^{-1}$). This finding indicates that there would be a gain in streamflow if the alien species are removed from riparian forests and rehabilitated back to their natural state.

Key Words: Sap flow, transpiration, indigenous trees, introduced trees, upscaling

1 Introduction

While extensive research has been undertaken on the water-use of terrestrial ecosystems in South Africa, little is known about riparian tree water-use and growth of both indigenous and introduced tree species. This knowledge gap, as well as the poor ecological condition of South African riparian habitats, has led to uncertainty and contention over riparian rehabilitation techniques. The deep fertile soils, with high soil moisture contents associated with riparian areas, make them ideal for plant establishment and growth (Everson *et al*., 2007). As such, these areas are extremely vulnerable to invasion by pioneer plant species, particularly alien species that have historically been introduced for commercial forestry. It is widely believed that riparian zone vegetation, which can be described as the interface between terrestrial and aquatic ecosystems (Richardson *et al*., 2007), has a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation rooting systems to the water table. Most riparian trees are phreatophytic, meaning they have access to a permanent source of water because their rooting system is within the shallow ground water.

Through the process of evaporation and transpiration, riparian vegetation influences streamflow rates, ground water levels and local climates (Richardson *et al*., 2007). Vegetation along riverbanks filter surface and subsurface water moving across and through the soil to the river channel. This helps to maintain channel water quality, by regulating the water temperature (through shading), bank stability and turbidity and traps debris (Askey-Dorin *et al*. 1999). Riparian vegetation can access a wide range of water sources within the riparian zone, which includes rainfall, soil water, stream water and groundwater (O'Grady *et al*., 2005). Commerical forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). Introduced tree species can change the natural landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrology, as well as changing the physical and chemical composition of the soil (Joshi *et al*. 2004; Le Maitre *et al*. 1996; Tabacchi *et al*. 2000). For these reasons, invasive alien plants, particularly introduced commercial trees, are considered to be a major threat to biodiversity globally (Reid *et al*. 2009; Solarz 2007; Wal *et al*. 2008). There is a widespread belief in South Africa and globally that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programmes. This is based on observations that indigenous trees are generally slow growing, and that growth and water-use are broadly linked (Everson *et al*., 2008; Gush, 2011). However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees in South Africa. A global review of water-use differences between introduced invasive and indigenous (native) plants at the leaf, plant and ecosystem scale (Cavaleri and Sack, 2010), indicates that invasive plants use up to 136 % more water than the indigenous species at the leaf scale (Baruch and Fernandez, 1993; Dixon *et al*., 2004; Pratt and Black, 2006). At the plant scale there is a diverse range in water-use ranging from the invasive species using 100 % less to 150 – 300 % more water than the indigenous species (Cleverly *et al*., 1997; Nagler *et al*., 2003; Kagawa *et al*., 2009). At the ecosystem scale studies indicate that invasive species use 189 % more water than indigenous dominates areas, particularly in tropical moist forests (Nosetto *et al*., 2005; Yepez *et al*., 2005; Fritzsche *et al*., 2006). In the high rainfall areas of South Africa, invasive alien plants growing in riparian areas are estimated to reduce annual streamflow by 523 x 106 m^3 with a predicted annual reduction estimated to be as high as 1 314 x 106 m^3 if allowed to reach a future fully invaded state (Cullis *et al*., 2007). Management of invaded riparian zones can result in hydrological gains disproportionately greater than the catchment area affected, with up to three times more streamflow yield than upslope areas (Scott and Lesch, 1996; Scott, 1999).

For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are often used without proper validation, and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. With the on-going development of micrometeorological techniques, it is possible to accurately quantify the various components of the water cycle over various terrestrial surfaces. The use of micrometeorological techniques is largely dependent on location, time constraints and available funds. However, due to continuous research by experts, the implementation of these techniques has become faster and more easily understood. In addition, comparisons between techniques and up-scaling have become possible, allowing for greater freedom in the choice of techniques and the length of measurement (Savage *et al*., 2004; Jarmain *et al*., 2008). Sap-flux density studies have been undertaken locally and internationally, and are well documented. Sap flux density measurements give precise information on flow directions as well as spatial and temporal flow distribution (Vandegehuchte and Steppe, 2013). The heat pulse velocity (HPV) method is the most accurate of the available methods when compared against gravimetric methods (Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013).

The Buffeljags River site in the Western Cape has been an ecological research site since 2006 and forms part of a selective thinning experiment designed to assist Working for Water (WfW) clearing programmes. The government-funded WfW programme clears catchment areas of invasive alien plants with the aim of restoring hydrological functioning while also providing poverty relief to local communities (Turpie *et al*., 2008). The aim of this study was to measure tree water-use to quantify the potential hydrological benefit of these forest management practices, improve the realistic modelling of these management approaches and provide guidelines towards suitable indigenous alternatives.

1.1 The study area

The Buffeljags river flows southwards along the Langeberg West mountain range into the Buffeljags dam. The Buffeljags river study area is at latitude 34˚00’15”S and longitude 20˚33’58”E (Figure 1), approximately 95-110 m above mean sea level. The research area is within Quaternary Catchment (QC) H70E and falls under the Western Cape Afrotemperate forest type which is characterized by very small forest patches occuring along boulder screes consisting of streams, gorges and mountain slopes (Geldenhuys, 2010). The surrounding vegetation type is south Langeberg sandstone fynbos (Mucina and Rutherford, 2011). The Langeberg Mountains consist of Table Mountain Sandstone/quartzite (north of the Buffeljags River) with a ridge of shales to the south of the river. The soils are characterised by structureless sands, a result of previous alluvial deposition.The climate is typical of the Western Cape with hot summers and cold winters. However, the rainfall is fairly evenly spread throughout the year. The long-term (137 year record) mean annual precipitation (MAP) at Buffeljags River is 636 mm. The daily maximum temperatures range from 17.1 °C in July to 27.5 °C in January. The mean daily minimum temperature is 15 °C in February and 5 °C in July. A 99 ha riparian forest occurs along the river with 75 ha of invaded forest (lower reach) and 24 ha of pristine indigenous forest (upper reach) (Figure 1), comprising of species such as *Celtis africana*, *V. lanceolata*, *Prunus africana*, *Rapanea melanophloeos* and *Afrocarpus* (*Podocarpus falcatus*)**.** The stand height ranged from 3 to 15 m in the indigenous stand and 11 to 17 m in the alien stand. The surrounding vegetation is mountainous fynbos and renosterveld.

Historically *A. mearnsii* trees were planted for small scale uses (firewood and building material) on the nearby farms. Working for Water cleared most of the alien trees which have since grown back over the last 15 years. Currently the invasion extends approximately one kilometer along the river.

1.2 The study sites

Three representative trees within the indigenous stand were instrumented for monitoring sapflow. These trees included an understorey tree (*Rothmania capensis*), one medium (*V. lanceolata*) and one large evergreen tree (*V. lanceolata*) that were most common throughout the stand. The leaf area index (LAI) within this stand was 3.6 throughout most of the season with a slight reduction during the winter months. Downstream of this site, within the alien stand (Figure 1), three *A. mearnsii* trees were instrumented over the three year study period. In a similar way, small, medium and large diameter classes were chosen to assist in the up-scaling of single tree transpiration measurements of the *Acacia* trees. The LAI of the *Acacia* stand was 3.1 during the summer months and 2.8 during the winter months. Two indigenous tree clusters within the alien stand were also instrumented. The *V. lanceolata* cluster contained two medium and one large diameter class trees (LAI of 3.4) while the *C. africana* cluster contained two large diameter class trees with a LAI of 3.3 in the summer months and 1.8 during the winter months. The LAI provided an indication of the seasonality of the trees and the light variations between the sites.

Both the indigenous and introduced alien stands were in a climax state with most of the canopy trees falling into the medium or large size classes. Although there were many smaller trees (excluding trees with a Ø < 5 mm), these did not contribute significantly to the total transpiration as they were shaded out by the climax trees. An overview of the individual tree characteristics has been provided in Table 1. Variations in moisture content were possibly due to the different ages and sizes of the trees measured (variations in sap wood depth and active xylem concentration).

2 Methods

A meteorological station was established on the 25th of January 2012 at Buffeljags River in a nearby planted *Eragrotis plana* field, 1.6 km from the indigenous site. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), at a height of 1.2 m from the ground was measured with additional measurements at a height of 2 m for air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp and Zonen, Delft, The Netherlands) windspeed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA). These were measured at a 10 second interval and the appropriate statistical outputs were recorded every hour.

A Heat Pulse Velocity (HPV) system using the heat ratio algorithm (Burgess, 2001) was set up to monitor long-term sapflow on all of the selected trees over a three year period. The instrumentation is described by Clulow *et al*. (2013) and included a 0.5 second heat source (sapflow trace) in the form of a line heater. A pair of type T-thermocouple probes was used to measure pre- and post-temperatures 5 mm above (downstream) and below (upstream) of the heater probe (Clulow *et al*., 2013). Hourly measurements (CR1000, Campbell Scientific Inc., Logan, Utah, USA) were captured over the three year monitoring period (January 2012 to March 2015). Monthly checks were undertaken to adjust probe depths in order to account for radial stem growth if required.

An assessment of the bark and sapwood depth was undertaken on the selected trees using an increment borer. This assessment assisted in determining the HPV probe insertion depths and the calculation of sapwood area. The heat pulse velocity (V_h) was calculated from:

$$V_h = \frac{k}{x} \ln\left(\frac{V_1}{V_2}\right) 3600 \qquad (1)$$

where, k is the thermal diffusivity of green (fresh) wood, x is the distance (5 mm) above and below the heater (representing upstream and downstream), and v_1 and v_2 are increases in the downstream and upstream temperatures (from initial average temperatures) respectively. A thermal diffusivity (k) of 2.5 $\times 10^{-3}$ $cm^2 \cdot s^{-1}$ (Marshall 1958) was used. Wounding or damaged xylem (non-functional) around the thermocouples was accounted for using wound correction coefficients described by Swanson and Whitfield (1981). Sap velocities were then calculated by accounting for wood density and sapwood moisture content as described by Marshal (1958). Finally, sap velocities were converted to tree water-use (Q_{tree}) or sap flow ($L \cdot hr^{-1}$) by calculating the sum of the products of sap velocity and cross-sectional area for individual symmetrical tree stems (Clulow *et al*., 2013).

Tree growth was recorded every two months throughout the monitoring period by measuring diameter at breast height with a dendrometer, and canopy height using a VL402 hypsometer (Haglöf, Sweden). Leaf area index (LAI-2200, LI-COR, Lincoln, Nebraska, USA) was measured monthly under each stand. Riparian forests typically have a narrow canopy with limited aerodynamic fetch, which excludes techniques such as eddy covariance and scintillometry being used to support the up-scaling of point water-use measurements to stand water-use values. Due the homogenous composition of the alien stand and the dominance of *Vepris* and *Celtis* species within the indigenous stand, a methodology was followed based on recent up-scaling studies (Ford et al., 2007; Miller et al., 2007). In addition, detailed stem density data were available for the site due to extensive ongoing ecological research (Atsame-Edda, 2014). Medoid (representative of the population) trees were selected for sap flow measurement. This included the most commonly occurring alien and indigenous species (canopy and understorey) and a range of size classes for each species. A species density analysis was undertaken (Ø > 50 mm) in replicated 400 m^2 plots per site. A relationship between total tree water-use (Q_{tree} – $L \cdot day^{-1}$) and each representative size and species class was identified. This allowed for the estimation of the stand water flux (Q_{stand}) which was divided by the plot area (400 m^2) in order to obtain comparative units between the indigenous and alien stands ($L \cdot day^{-1} \cdot ha^{-1}$). These values were then accumulated to annual values so that the effect of alien and indigenous (evergreen and deciduous) stands on the water balance could be quantified throughout a hydrological year.

The *A. mearnsii* site had a thin litter layer consisting mostly of broken branches, bark and leaves compared with the indigenous site which had a thicker litter layer with a large amount of organic matter accumulated from the various tree species and understorey vegetation. Volumetric soil water contents were measured hourly at both the indigenous and alien sites (concurrent to the HPV measurements) with three time domain reflectometry (TDR) probes (Campbell Scientific. CS 615) installed horizontally at each site at depths of 0.1 m, 0.3 m and 0.5 m. The TDR probes were connected to spare channels on the CR1000 datalogger of the HPV system. With hourly volumetric water content measurements, the response of trees to rainfall events, or stressed conditions, were monitored and supported the interpretation of the HPV measurements. An observation borehole was installed at the site to monitor the groundwater recharge as well as to confirm the assumption that all the trees within the riparian forest had direct access to groundwater. Soil samples were taken to determine the distribution of roots, bulk density and soil water content. These samples (taken at various depths throughout the profile) were weighed before and after oven drying to determine the soil characteristics.

3 Results

3.1 Weather conditions during the study period

The MAP over the three year study was significantly higher than the long-term average (636 mm) by 300-500 mm (2012 to 2014 being 1017, 902 and 1127 mm respectively). The rainfall distribution was variable (lacking a seasonal trend) throughout the three years with a mean monthly value of 85 mm (Figure 2). There were numerous days of high hourly rainfall (to a maximum of 30mm·h^{-1} and 102 mm·day^{-1}) demonstrating the prevalence of high intensity storms at the site (Figure 3). The solar radiation peaked at 34 MJ·m^{-2}·day^{-1} following the same seasonal trend to that of the daily minimum and maximum temperatures.

The relative humidity (RH) ranged from 20 % to 90 %, with little seasonal trend. During periods of high solar radiation, the atmospheric demand was high and correlated to peaks in transpiration rates. An average daily temperature of 22.1 ºC was recorded at Buffeljags River in the summer months. During these months, daily maximum temperatures occasionally exceeded 40 ºC. During the winter months, the temperatures averaged 12.1 ºC due to numerous days with low solar radiation, such as during rainfall events and cloudy days, and would likely result in little to no transpiration occurring. The daily reference total evaporation (ET_o), derived from data captured at the meteorological station, averaged approximately 1 mm in the winter period to 4 mm during summer. The daily ET_o peaked at 7.5 mm, which correlated to peaks in measured transpiration.

3.2 Tree water-use

For comparative purposes the water-use of similar sized *Vepris* and *Acacia* trees were compared during the wet and the dry seasons (Figures 4 and 5). During the summer month of January, the *V. lanceolata* tree water-use exhibited seasonal curves indicative of the clear sunny days and high correlation to the solar radiation. The medium sized *V. lanceolata* (Ø 17.4 cm) used an average of 24 L·day^{-1} during the summer months and an average of 8 L·day^{-1} during the winter months (Figure 4). The medium sized *A. mearnsii* (Ø 16.7 cm) used an average of 10 L·day^{-1} in the winter months, similar to that of the *V. lanceolata*. In the summer months, the *A. mearnsii* used an average of 39 L·day^{-1}, significantly higher than the indigenous tree (Figure 5). During significant rainfall periods (> 5 mm) there was little to no water-use in both trees due to the low evaporative demand and the wet canopy.

Individual whole tree water-use was significantly reduced in winter (May and June) for most of the trees, dropping by approximately 75 %. This was attributed to fewer daylight hours in the winter months which resulted in less available energy at this time of year to drive the transpiration process. From November 2012 to March in 2013, all species showed a significant increase in water-use during this hot summer period. The water-use in the *A. mearnsii* trees showed a distinct peak in transpiration during the months of March 2012, September 2012 and February 2013. During March 2012, the high average temperature (21.5 ºC), a 76 mm rainfall event and high daily vapour pressure deficits (VPD) (average of 1.26 kPa) contributed to a high atmospheric demand. On cloudless days with a high VPD and high soil water, the trees would be expected to use more water. The average daily sap flow ranged from 15 L·day^{-1} in the smaller class tree, 25 L·day^{-1} in the medium class tree and 39 L·day^{-1} in the large class tree (Tables 1 and 2).

The daily summer water-use of two of the *V. lanceolata* trees (Table 2) in the upper indigenous stand showed high water-use with an average of 19 L·day^{-1} (medium class) and 37 L·day^{-1} (large class). The high water-use in the large tree was ascribed to its size and deep rooting system which is presumed to have had easy access to ground water at this site due to the proximity to the river (10 m horizontal distance). This was verified with the borehole levels and a root analysis at the site. The water level ranged from 3.2 m to 4.8 m at the site where roots were observed to 5 m, while installing the borehole. The water-use of the small understorey tree *R. capensis* had a much lower water-use (average of 8 $L \cdot day^{-1}$) which indicated that although the understorey used less water, it still made a significant contribution to the water balance given the abundance of understorey species in the indigenous forest.

The *C. africana* trees displayed a high water-use during the summer period. As this is a deciduous tree, no water was used during leaf fall in winter. The largest *C. africana* tree had a canopy area of 75 m^2 and was the largest tree at the site. Approximately 37 700 L of water was transpired by this tree annually during the measurement period (Table 2). Given that this species is deciduous, it is important to note that this tree uses a high volume of water in summer when water resources are usually limited. However, in a summer rainfall region, like eastern South Africa, this tree would not use water during the low flow season when water resources are limited. This is important for management decisions throughout rainfall zones in South Africa.

The indigenous cluster in the alien site had a LAI of 3.4, which was higher than the LAI of 3.1 under the nearby *A. mearnsii* trees. The indigenous trees in the upper reach indigenous site had an LAI of 3.6. Although the summer water-use was higher in the introduced trees, the radial sapwood area was larger in the indigenous trees (up to 413 cm^2) than the introduced trees (up to 171 cm^2). Trees with the highest sap velocities are therefore not necessarily those with highest whole tree water-use. However, this does indicate that the alien trees are more effective users of water, relative to their sapwood area.

3.3 Soil profile and water content

The volumetric water content (VWC) in the alien stand at Buffeljags River was very low, dropping to 7 % during dry periods (Figure 6). During high rainfall events the soil VWC exceeded 20%, showing a rapid but short response to rainfall. This indicates that the soil water moves through the soil profile rapidly with very little water being stored in the profiles, particularly in the lower profile. The soils had a dry bulk density (ρb) of 1.58 $g.cm^{-3}$, a particle density ($\rho_{particle}$) of 2.66 $g.cm^{-3}$ and a porosity 0.42, typically characteristic of sandy soils. The drying curve, after an isolated event, took on average 22 hours from saturation to the expected field capacity (Figure 4). *Acacia* stands are known to have deep rooting systems, with observations of greater than 8 m in South Africa (Everson *et al*., 2006). This suggests that during dry periods, this stand can access water from deeper layers in the soil profile.

In the indigenous stand (Figure 7), the middle TDR probe (0.3 m) showed the highest water content. During the warmest period (December to April) there was very little water in the profile (even after rainfall events). This would suggest that the deeper roots from the indigenous species were readily using water below the TDR probe measurement depths as there was no correlation between transpiration and change in VWC. In contrast, the alien stand upper soil profile water content responded to rainfall events suggesting that interception storage (including throughfall and stemflow that contribute to litter catch) played a significant role when comparing these stands. After an isolated rainfall event, the drying curve, of the soil profile at the indigenous site took much longer (up to one week) from its peak to the driest level. The average water content was 5 %, lower than the alien stand, suggesting a difference in root activity given the same soil characterisics.

The VWC at both sites did not respond significantly to rainfall events under 5 mm unless during consecutive events. The average water table depth, measured using an observation borehole, ranged from 5.2 m below the ground surface during the dry season to 3.2 m below the ground surface during the wet season (excluding extreme events). The water table recharge time showed a strong relationship to the soil wetting and drying response time recorded at both sites. In conclusion, both the indigenous and introduced stands are energy limited rather than water limited as both had root contact with the water table.

3.4 Upscaling tree water-use

The results obtained from the research area were used to determine an actual annual water-use per unit area for both the invaded alien and pristine indigenous tree stands (Figure 8). Using the stem density per size class, stands of forest were compared rather than individual trees. A closed canopy was assumed. The upscaled water-use for a three year average of the *A. mearnsii* stand was 5 879 $L \cdot ha^{-1}$ for the small size class, 7 639 $L \cdot ha^{-1}$ for the medium size class and 9 981 $L \cdot ha^{-1}$ for the large size class. When upscaled for all species and size classes for the three year average, the total stand water-use was approximately 5.85 $ML \cdot ha^{-1} \cdot year^{-1}$ (585 $mm \cdot yr^{-1}$). This was 57 % of the average annual precipitation recorded during the monitoring period (1021 mm).

The annual water-use of the indigenous stand was 1 209 $L \cdot ha^{-1}$ for the small size class, 6 321 $L \cdot ha^{-1}$ for the medium size class and 18 900 $L \cdot ha^{-1}$ for the large size class. The upscaled indigenous stand used 1.01 $ML \cdot ha^{-1} \cdot year^{-1}$ (101 $mm \cdot yr^{-1}$). Based on these results we concluded that the alien stand uses nearly six times more water per unit area annually than the indigenous stand. This roughly correlated to the growth rate of each stand, where the stem breast height diameter increase over the study period (recorded on each tree measured) was between three to eight times faster than similar sized indigenous trees.

The inter-species and size class water-use variations, particularly within the indigenous stand, highlight the importance of good replications of a representative sample tree species and size classes. These results also highlight that individual indigenous trees, such as the *C. africana*, can use more water than an individual alien *A. mearnsii* tree. An example of this is the largest *Celtis* using 14 000 L more water annually than the largest *A. mearnsii*. However, the *C. africana* tree had a much larger diameter and had a large canopy area under which no other trees grew, whereas approximately ten medium sized *A. mearnsii* trees could occupy the same area as this particular tree. The importance of upscaling using representative samples of species and size classes is clearly demonstrated by the study.

4 Discussion and Conclusion

There is a widespread belief in South Africa that indigenous tree species, in contrast to introduced tree species, use less water and should be planted more widely in land rehabilitation programmes (Olbrich et al., 1996; Dye et al., 2001; Everson et al., 2007; Dye et al., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015). A review of relevant literature revealed a general paucity of information relevant to both indigenous and introduced tree water-use, the methods of replication and the techniques used. Internationally, improved HPV techniques have been used on various vegetation types and the accuracy of these studies has been validated using gravimetric methods (Granier and Loustau, 2001; Burgess *et al*., 2001; O'Grady *et* al., 2006; Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013; Uddin and Smith, 2014). International studies indicate that at the plant scale, introduced invasive species can use from 100 % less water to between 150 to 300 % more water than indigenous landscapes. Furthermore, there can be a significant disconnect between up-scaling plant scale measurements to an ecosystem scale (Cavaleri and Sack, 2010). In South Africa, the HPV technique has been shown to provide accurate estimates of sap flow in both introduced tree species such as *A. mearnsii* and *Eucalyptus grandis*, and indigenous tree species such as *Podocarpus henkelii* and *C. africana* (Smith *and* Allen, 1996; Dye *et al*., 2001; Everson *et al*, 2007; Dye *et al*., 2008). A key recommendation from the literature, which has been emphasized in a recent study by Gush and Dye (2015), is that more indigenous tree stand management research is needed in South Africa.

Spatial estimates of evaporation and transpiration are required but are difficult to obtain in remote areas with limited aerodynamic fetch. A large capital and human effort was invested towards this study in order to extend the monitoring period, with a range of species and replicates. This allowed for an accurate comparison of indigenous and introduced tree water-use. The Buffeljags River site is unique in that it is one of very few sites within South Africa with an extensive rehabilitation programme that aims to assist WfW and similar clearing programmes. The results showed that individual tree water-use varies depending on size and species. Up-scaled comparisons showed that stem density is important to the accurate representation of stand water-use. A stand of introduced *A. mearnsii* can use up to six times more water annually than a mixed indigenous stand. This finding is significant in that it provides clear evidence to justify the highly expensive clearing programmes, which have in the past lacked quantifiable data on the potential hydrological benefits of alien plant clearing. The results also indicate that rehabilitation or clearing programmes need to consider the seasonal rainfall variability of a site as planting of deciduous indigenous trees may provide larger benefits in summer rainfall areas due to no transpiration during periods when water resources are limited.

This study provides an ideal opportunity to validate remotely sensed ET data which could also be used to identify spatial variations in vegetation water-use. This future research will allow for the broader extrapolation of alien plant water-use and benfits of clearing ripaian zones to similar areas outside of the immediate study area. Results may be used to further validate transpiration simulations from hydrological models, particularly in riparian areas.

Acknowledgements. The research presented in this paper forms part of an unsolicited research project (Rehabilitation of alien invaded riparian zones and catchments using indigenous trees: an assessment of indigenous tree water-use) that was initiated by the Water Research Commission (WRC) of South Africa. The project was managed and funded by the WRC, with co-funding and support provided by the Department of Economic Development, Tourism and Environmental Affairs (EDTEA). The land owners, Brian and Janet Kilpen of Frog Mountain Inn, are acknowledged for allowing field work to be conducted on their property. Assistance in the field by Dr Terry Everson, Matthew Becker and Liandra Scott-Shaw is much appreciated.

5 References

Askey-Dorin, M., Petit, N., Robins, L., and McDonald, D.: The role of vegetation in riparian management. In: Riparian Land Management Technical Guidelines. Vol. 1. Principles of Sound Management. Eds. S. Lovett and P. Price. LWRRDC Canberra. pp. 97-120, 1999.

Atsame-Edda, A.: Regeneration dynamics of natural forest species within a stand of the invasive alien *Acacia mearnsii* along the Buffeljagsrivier, Swellendam, South Africa. MSc Thesis. Stellenbosch University, 2014.

Baruch, Z., and Fernandez, D.S.: Water relations of native and introduced C4 grasses in a neotropical savanna. Oecologia 96:179–185, 1993.

Burgess, S. O., Adams, M. A., Turner, N. C., Beverly, C. R, Ong, C. K., Khan, A. A. H., and Bleby, T. M.: An improved heat pulse method to measure low and reverse rates of sap flow in woody plants, Tree Physiol., 21, 589-598, 2001.

Cavaleri, M.A., and Sack, L.: Comparative water use of native and invasive plants at multiple scales: a global meta-analysis. Ecology, 91(9), 2010, pp. 2705–2715, 2010.

Cleverly, J. R., Smith, S. D., Sala, A., and Devitt, D.A.: Invasive capacity of Tamarix ramosissima in a Mojave Desert floodplain: the role of drought. Oecologia 111:12–18, 1997.

Clulow, A.D., Everson, C.S., Price, J.S., Jewitt, G.P.W., and Scott-Shaw, B.C.: Water-use dynamics of a peat swamp forest and dune forest in Maputaland, South Africa, Hydrol. Earth Syst. Sci., 17, 2053-2067, 2013.

Cullis, J., Görgens, A., and Marais, C.: A strategic study of the impact of invasive alien vegetation in the mountain catchment areas and riparian zones of South Africa on total surface water yield. Water SA 33 (1) 35-42, 2007.

Dixon, P., Hilton, M., and Bannister, P.: *Desmoschoenus spiralis* displacement by *Ammophila arenaria*: the role of drought. New Zealand Journal of Ecology 28:207–213, 2004.

Dye, P. J.: Modelling growth and water-use in four Pinus patula stands with the 3-PG process-based model, Southern African Forestry Journal, No. 191(53-63), 2001.

Dye, P. J., Gush, M. B., Everson, C. S., Jarmain, C., Clulow, A., Mengistu, M., Geldenhuys, C. J., Wise, R., Scholes, R. J., Archibald, S., and Savage, M. J.: Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions, Water Research Commission Report No. 361/08, ISBN 978-1-77005-744-9, Water Research Commision, Pretoria, South Africa, 156 pp., 2008.

Everson, C. S., Gush, M. B., Moodley, M., Jarmain, C., Govender, M., and Dye, P.: Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources, Water Research Commission Report No. 1284/1/07, ISBN 978-1-77005-613-8, Pretoria, South Africa, 92 pp., 2007.

Ford, C.R., McGuire, M.A., Mitchell, R.J. and Teskey, R.O.: Assessing variation in the radial profile of sap flux density in Pinus species and its effect on daily water-use. Tree Physiol. 24, 241-249, 2004.

Fritzsche, F., Abate, A., Fetene, M., Beck, E., Weise, S., and Guggenberger, G.: Soil-plant hydrology of indigenous and exotic trees in an Ethiopian montane forest. Tree Physiology 26:1043–1054, 2006.

Geldenhuys, C. J.: National forest types of South Africa: SA Forestry Magazine, Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa, 2010.

Granier, A., Loustau, D. and Bréda, N.: A Generic Model of Forest Canopy Conductance Dependent on Climate, Soil Water Availability and Leaf Area Index. Annuals of Forest Science. 57, 755-765, 2001.

Gush, M. B. and Dye, P. J.: Water-use Measurements of Selected Woodland Tree Species within the Kruger National Park. CSIR, % Agrometeorology, School of Environmental Sciences, University of KwaZulu-Natal, Scottsville, South Africa, 2008.

Gush, M. B. and Dye, P. J.: Water-Use Efficiency Within a Selection of Indigenous and Exotic Tree Species in South Africa as Determined Using Sap Flow and Biomass Measurements. CSIR, % Agrometeorology, School of Environmental Sciences, University of KwaZulu-Natal, Scottsville, South Africa, 2009.

Gush, M. B.: Water-use, growth and water-use efficiency of indigenous tree species in a range of forest and woodland systems in South Africa. PhD dissertation, Department of Botany, University of Cape Town, 2011.

Gush, M. B., de Lange, W.J., Dye, P.J. and Geldenhuys, C.J.: Water-use and Socio-Economic Benefit of the Biomass of Indigenous Trees Volume 1: Research Report, 2015.

Jarmain, C., Everson, C.S., Savage, M.J., Clulow, A.D., Walker, S. and Gush, M.B.: Refining tools for evaporation monitoring in support of water resource management. Water Research Commission Report No. 1567/1/08. Water Research Commision, Pretoria, RSA, 2008.

Jewitt, G.: Integrating blue and green water flows for water resources management and planning, Physics and Chemistry of the Earth, Parts A/B/C 31(15–16), 753-762, 2006.

Joshi, C., de Leeuw, J., and van Duren, I.C.: Remote sensing and GIS applications for mapping and spatial modelling of invasive species. Pages 669-677. ISPRS, Istanbul, Turkey, 2004.

Kagawa, A., Sack, L., Duarte, K. and James, S.A.: Hawaiian native forest conserves water relative to timber plantation: Species and stand traits influence water-use. Ecological Applications 19:1429–1443, 2009.

Le Maitre, D.C., van Wilgen, B.W., Chapman, R.A., and McKelly, D.H.: Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. Journal of Applied Ecology 33, 161–172, 1996.

Marshall, D. C.: Measurement of sap flow in conifers by heat transport. Plant Physiology, 33, 385-396, 1958.

Miller, G.R., Xingyuan, C., Yoram, R., and Baldocchi, D.D.: A new technique for upscaling sap flow transpiration measurements to stand or land use scale fluxes. Civil and Environmental Engineering, University of California – Berkeley, 2007.

Mucina, L., and Rutherford, M.C.: The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. South African National Biodiversity Institute, Pretoria, 2011.

Nagler, P. L., Glenn, E.P. and Thompson, T.L.: Comparison of transpiration rates among saltcedar, cottonwood and willow trees by sap flow and canopy temperature methods. Agricultural and Forest Meteorology 116:73–89, 2003.

Nosetto, M. D., Jobbagy, E.G. and Paruelo, J.M.: Landuse change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Global Change Biology 11:1101–1117, 2005.

O'Grady, A.P., Cook, P.G., Howe, P. and Werren, G.: An assessment of groundwater-use by dominant tree species in remnant vegetation communities, Pioneer Valley, Queensland. Aust. J. Bot, 2006.

Olbrich, B., Olbrich, K., Dye, P.J. and Soko, S. A.: Year-Long Comparison of Water-use Efficiency of Stressed and Non- Stressed E. grandis and P. patula: Findings and Management Recommendations. CSIR report FOR-DEA 958. CSIR, Pretoria, South Africa, 1996.

Pratt, R. B., and Black, R.A.: Do invasive trees have a hydraulic advantage over native trees? Biological Invasions 8: 1331–1341, 2006.

Reid, A.M.L., Morin, P.O., Downey, K., French, K.O., and Virtue, J.G.: Does invasive plant management aid the restoration of natural ecosystems? Biological Conservation 142:2342-2349, 2009.

Richardson, D.M., Rouget, M., Ralston, S.J., Cowling, R.M., VAN Rensburg, B.J., and Thuiller, W.: Species richness of alien plants in South Africa: Environmental correlates and the relationship with indigenous plant species richness. Ecoscience. 12, 391-402, 2005.

Scott, D.F.: Managing riparian zone vegetation to sustain streamflow: Results of paired catchment experiments in South Africa. Canadian Journal of Forest Research, 1999.

Scott, D.F., and Lesch, W.: The effects of riparian clearing and clearfelling of an indigenous forest on streamflow, stormflow and water quality. S. Afr. For. J. 175: 1-14, 1996.

Smith, D., and Allen, S.: Measurement of sap flow in plant stems. Journal of Experimental Botany, 47(12), 1833. http://dx.doi.org/10.1093/jxb/47.12.1833, 1996.

Solarz, W.: Biological invasions as a threat for nature. Progress in Plant Protection 47:128-133, 2007.

Steppe, K., De Pauw, D.J.W., Doody, T.M., Teskey, R.O.: A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. Laboratory of Plant Ecology, Department of Applied Ecology and Environmental Biology, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, 9000 Gent, Belgium, 2010.

Savage M.J., Everson, C.S., Odhiambo, G.O., Mengistu, M.G. and Jarmain, C.: Theory and practice of evaporation measurement, with a special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation, Water Research Commission Report No. 1335/1/04. Water Research Commission, Pretoria, RSA, 2004.

Swanson, R. H., and Whitfield, D. W. A.: A Numerical Analysis of Heat Pulse Velocity Theory and Practice, J. Exp. Bot., 32, 221-239, 1981.

Tabacchi, E., Lambs, L., Guilloy, G., Planty-Tabacchi, A.M., Muller, E., and de´Camps, H.: Impacts of riparian vegetation on hydrological processes. Hydrological Processes. 14, 2959–2976, 2000.

Turpie, J.K, Marais, C. and Blignaut, J.N.: The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecol. Econ. 65 (4) 788-798, 2008.

Vandegehuchte, M.W. and Steppe, K.: Sap-flux density measurement methods: working principles and applicability. Laboratory of Plant Ecology, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, 9000 Gent, Belgium, 2013.

Van Wilgen, B.W., Davies, S.J. and Richardson, D.M.: Invasion science for society: A decade of contributions from the Centre for Invasion Biology. S Afr J Sci.;110(7/8), Art. #a0074, 12 pages, 2014.

Wal, R.V.D., Truscott, A.M., Pearce, I.S.K., Cole, L., Harris, M.P., and Wanless, S.: Multiple anthropogenic changes cause biodiversity loss through plant invasion. Global Change Biology 14:1428-1436, 2008.

Yepez, E. A., Huxman, T.E., Ignace, D.D., English, N.B., Weltzin, J.F., Castellanos, A.E. and Williams, D.G.: Dynamics of transpiration and evaporation following a moisture pulse in semiarid grassland: a chamber-based isotope method for partitioning flux components. Agricultural and Forest Meteorology 132:359–376, 2005.

Table 1. Tree physiology and specific data required for the calculation of sap flow and up-scaling.

Indigenous Forest site (upper reach)	Wood density ($m^3\ kg^{-1}$)	Moisture fraction	Average wounding (mm)	Diameter (mm)	Size Class (S/M/L)	Representative Stem Density ($stems \cdot ha^{-1}$)
Rothmania capensis	0.59	0.45	2.8	125	S	120
V. lanceolata	0.63	0.42	3.7	134	M	65
V. lanceolata	0.66	0.42	3.4	199	L	24
Introduced/Alien Forest site (lower reach)						
Acacia mearnsii	0.54	0.89	3.2	121	S	650
Acacia mearnsii	0.73	0.47	3.2	167	M	200
Acacia mearnsii	0.61	0.71	3.0	194	L	50
Indigenous Cluster (lower reach)						
V. lanceolata	0.66	0.45	3.2	166	M	65
V. lanceolata	0.65	0.45	3.2	174	M	65
V. lanceolata	0.66	0.47	2.9	202	L	24
Indigenous Cluster (lower reach)						
C. africana	0.71	0.52	6.1	319	L	24
C. africana	0.71	0.50	6.0	422	L	24

*Note: The stem density was grouped as per size class

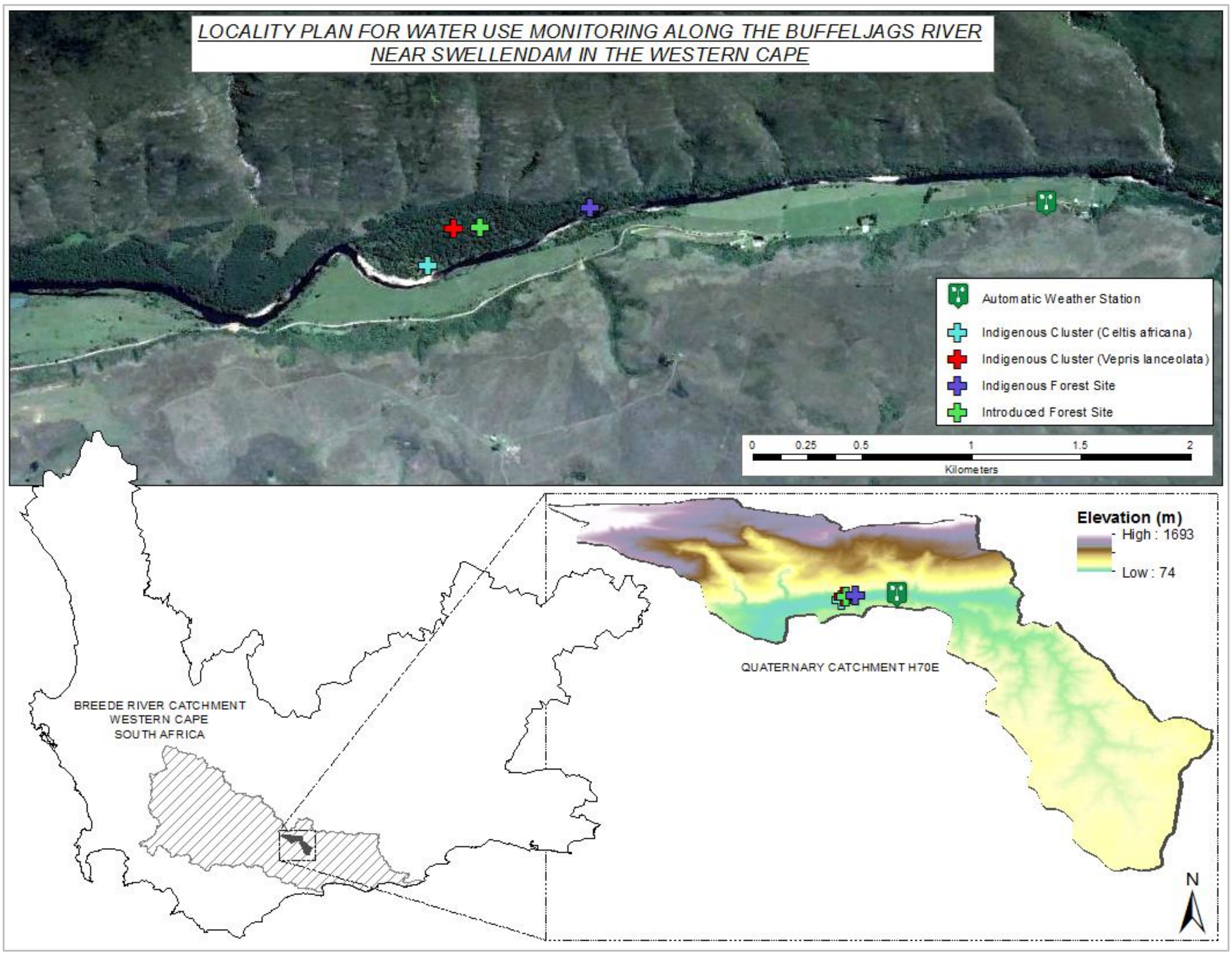

Figure 1. Location of the Buffeljags River research area within the Western Cape, South Africa

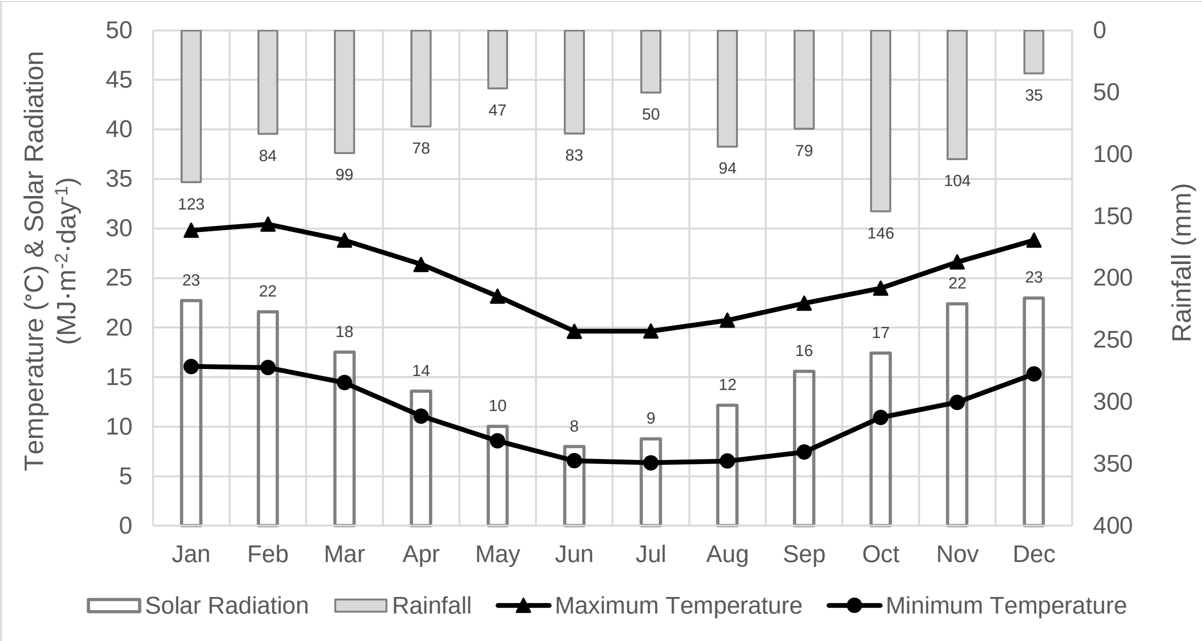

Figure 2. The monthly rainfall, monthly solar radiant density, and average monthly maximum and minimum air temperatures at Buffeljags River averaged over three years.

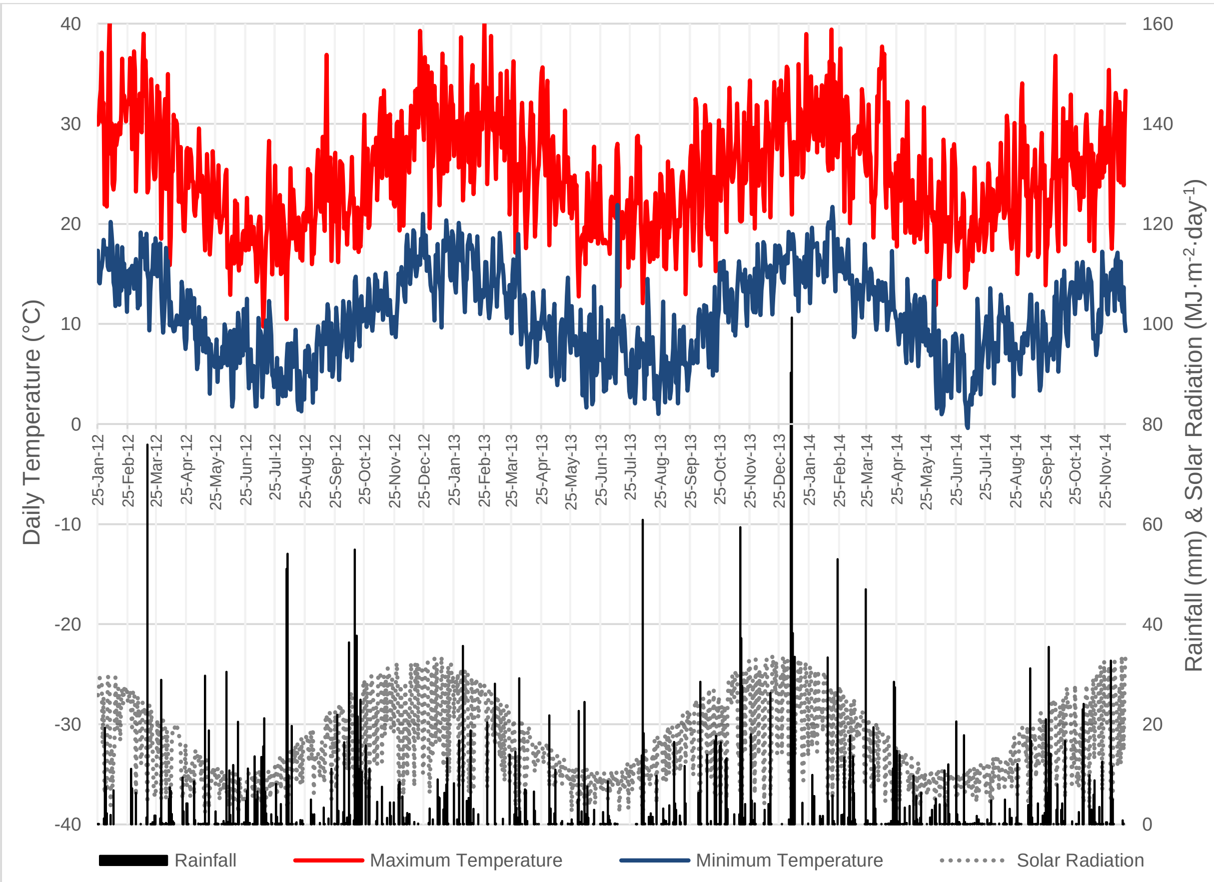

Figure 3. The daily rainfall, solar radiation and maximum and minimum air temperatures at Buffeljags River .

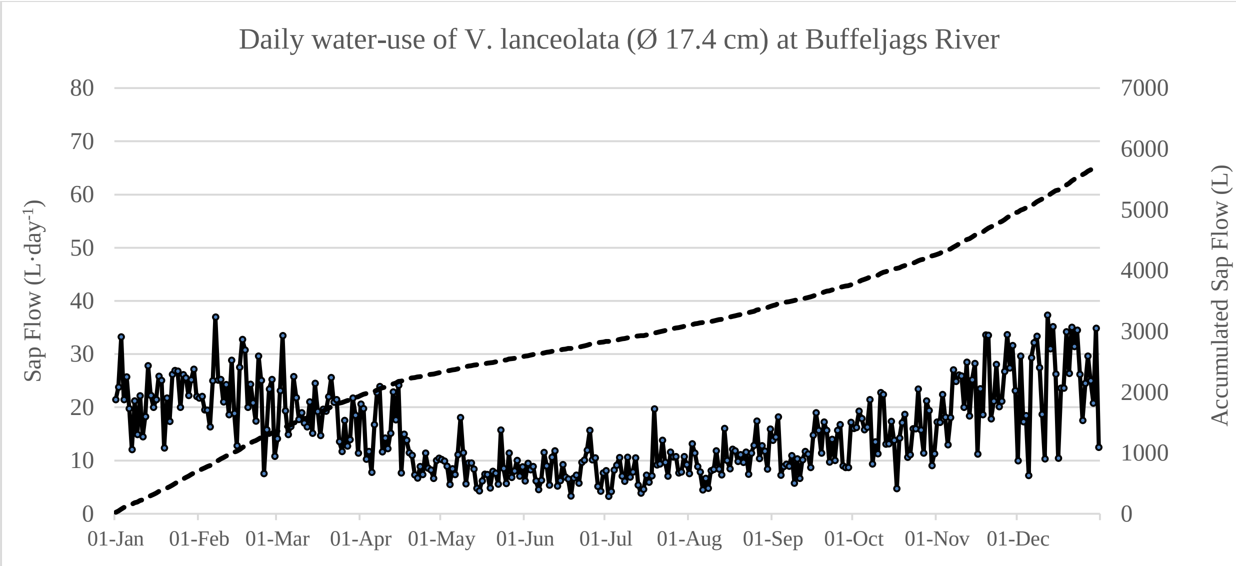

Figure 4. Sap flow (daily and accumulated) from a *V. lanceolata* in the lower reach stand at Buffeljags River (January 2012 to March 2015) averaged over three years

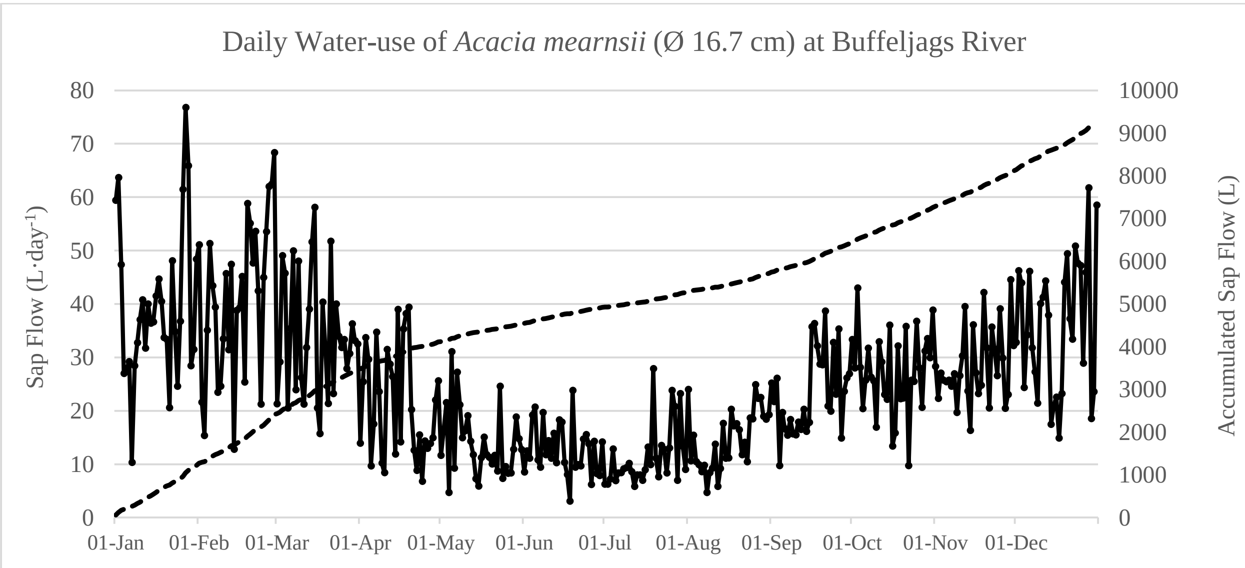

Figure 5. Sap flow (daily and accumulated) from an *Acacia mearnsii* in the lower reach stand at Buffeljags River (January 2012 to March 2015) averaged over three years

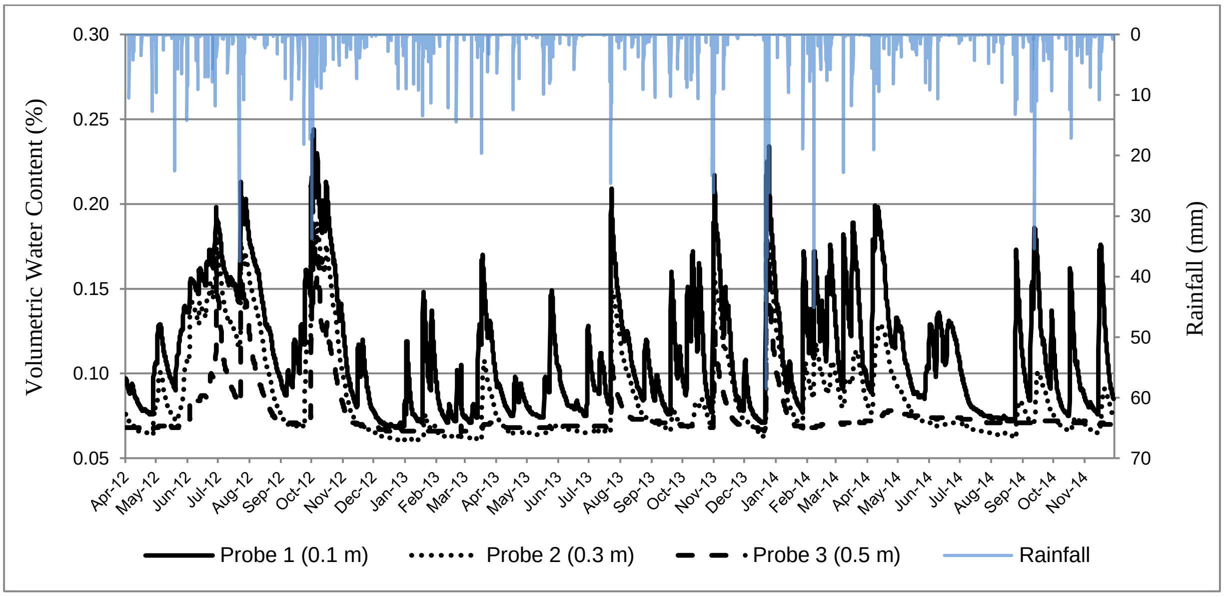

Figure 6. Hourly volumetric water content of the lower alien stand corresponding to the hourly rainfall at Buffeljags River

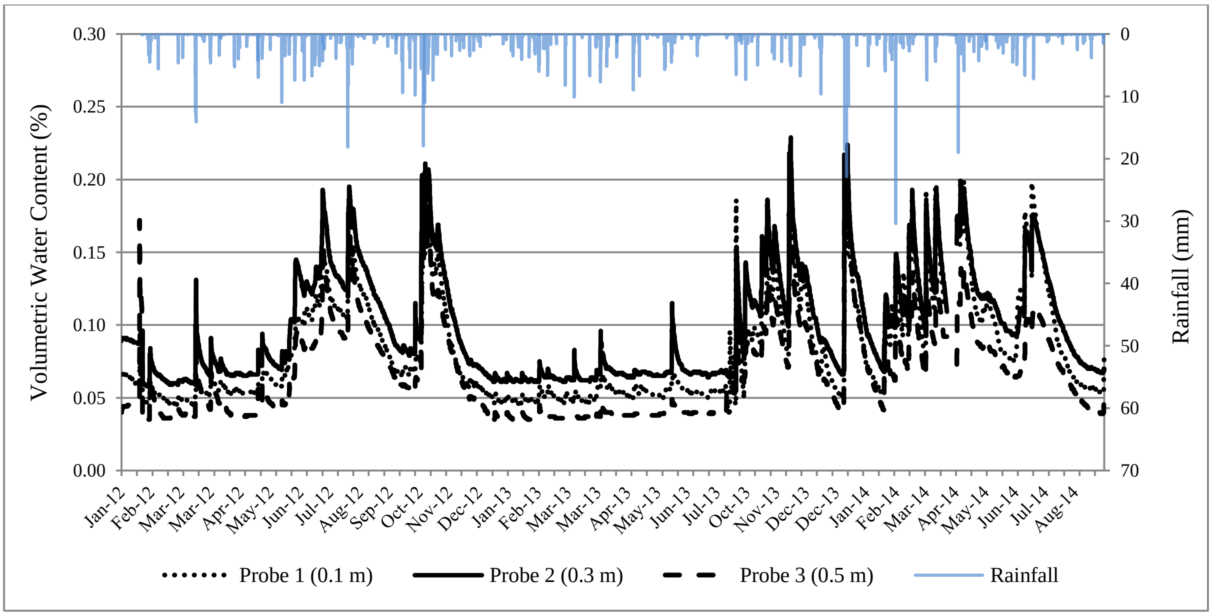

Figure 7. Hourly volumetric water content of the upper indigenous stand corresponding to the hourly rainfall at Buffeljags River

Table 2. Sap flow (daily and accumulated) for each species measured at Buffeljags River (January 2012 to March 2015)

Forest Type / Location	Species	Daily Average Summer Sap Flow (L)	Daily Average Winter Sap Flow (L)	Annual Accumulated Sap Flow (L)
Indigenous Forest site (upper reach)	*V. lanceolata*	19	7	6 534
	V. lanceolata	37	6	15 565
	Rothmania capensis	11	4	4 133
Introduced/Alien Forest site (lower reach)	*Acacia mearnsii*	25	8	9 226
	Acacia mearnsii	39	10	5 469
	Acacia mearnsii	32	9	7 207
Indigenous Cluster (lower reach)	*V. lanceolata*	14	6	5 725
	V. lanceolata	24	8	3 430
	V. lanceolata	39	14	9 174
Indigenous Cluster (lower reach)	*C. africana*	46	0	19 821
	C. africana	95	0	37 769

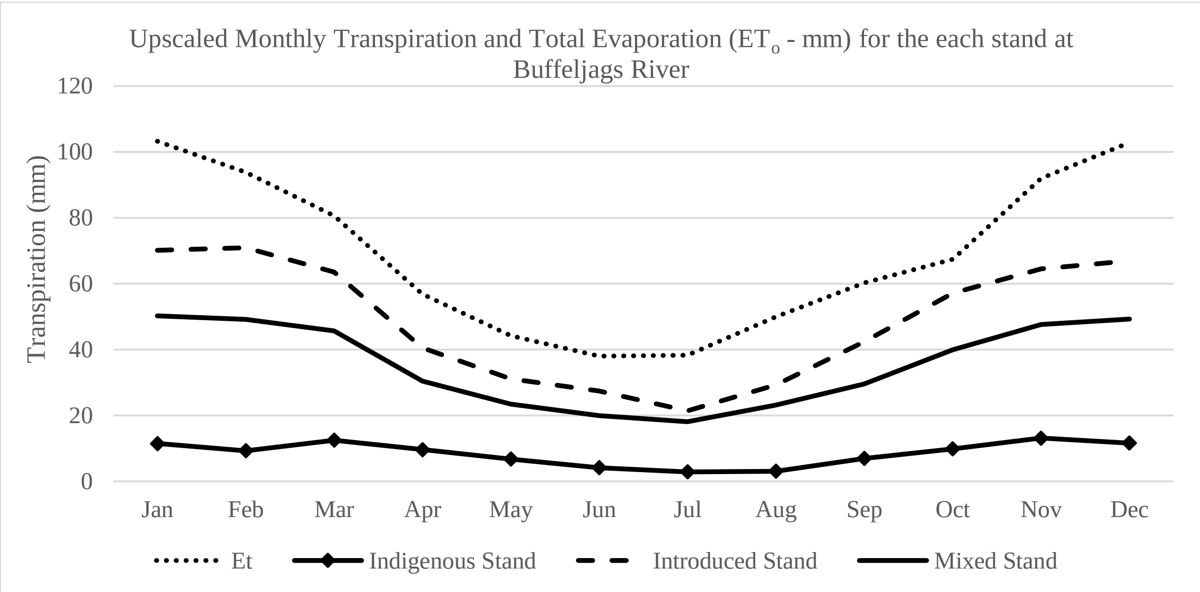

Figure 8. Upscaled monthly transpiration for the indigenous, introduced (*A. mearnsii*) and mixed stands in comparison to reference total evaporation